Wind-induced atmospheric escape: Titan

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[1] Rapid thermospheric flows can significantly enhance the atmospheric loss rates and structures of atmospheric coronae of planetary bodies. Using descriptions of atmospheric escape based on molecular kinetic models, we show that such flows at the exobase of Titan could significantly increase the calculated constituent thermal and nonthermal escape rates. In particular, we show here that the effect of thermospheric winds at the exobase cannot be ignored when calculating the escape of methane from Titan. Such enhancements are likely also relevant to Pluto and exoplanet atmospheres. **Citation:** Hartle, R. E., R. E. Johnson, E. C. Sittler Jr., M. Sarantos, and D. G. Simpson (2012), Wind-induced atmospheric escape: Titan, *Geophys. Res. Lett.*, *39*, L16201, doi:10.1029/2012GL052774.

1. Introduction

[2] Escape of the dominant constituents from Titan's atmosphere has been the subject of many recent studies [e.g., *Johnson et al.*, 2009]. The dominant atmospheric constituent at the homopause is N_2 at $\sim$95% followed by CH_4 at $\sim$2–3% with H_2 and other minor constituents below 1%. These diffusively separate having very different relative concentrations at the exobase, the region of interest here. The focus on Titan is, of course, the result of the Cassini mission, during which many flybys through its upper atmosphere have characterized the composition and structure of its thermosphere, exosphere and ionosphere. As reviewed in *Johnson et al.* [2009], a number of processes recently studied affect escape rates. These include thermal escape [*Cui et al.*, 2008, 2011], chemically induced escape [*De La Haye et al.*, 2007], slow hydrodynamic escape [*Strobel*, 2009; *Yelle et al.*, 2008], pickup ion loss and ionospheric outflow [*Ledvina et al.*, 2005; *Wahlund et al.*, 2005; *Hartle et al.*, 2006; *Sittler et al.*, 2009] and plasma-induced escape [*Shematovich et al.*, 2003; *Michael et al.*, 2005; *Bell et al.*, 2010; *Westlake et al.*, 2011]. As additional data is obtained on future flybys of Titan, the relative importance of the various escape processes should become clearer.

[3] One property of the atmosphere that contributes to escape that has not been applied yet is the effect of horizontal winds. *Hartle and Mayr* [1976, hereinafter HM], showed that horizontal winds generated in the thermosphere at exobase altitudes can significantly enhance escape rates. Such winds have been shown to be present by *Müller-Wodarg et al.* [2008, hereinafter M-WYCW], with a model that extends from the lower thermosphere, $\sim$1000 km, to exobase altitudes, $\sim$1450–1600 km. This model was calibrated to the observed Titan densities [*Waite et al.*, 2004, 2005] using the data from the Ion-Neutral Mass Spectrometer (INMS) on Cassini. Based on these densities, meridional, zonal and vertical winds were derived using a version of the Thermosphere General Circulation Model [*Müller-Wodarg et al.*, 2003, 2008]. They obtained peak horizontal speeds near the exobase of the order of $\sim$150 m s^{-1}. The INMS spatial composition data are suggestive of thermospheric temperatures ranging from $\sim$110–188 K [*Westlake et al.*, 2011]. For an average $\sim$142 K, the wind speed is about half the thermal speed for nitrogen molecules, about 40% for methane, and about 10% for hydrogen.

[4] The approach taken in this paper is to compare atmospheric escape in the presence of horizontal winds first to the Jeans escape flux from a static atmosphere and then to escape driven by nonthermal processes. We show that flux enhancements occur when horizontal winds at the exobase are included in the molecular speed distribution function. Comparison of these enhancements with their Jeans escape fluxes is appropriate since a thermosphere-exosphere Monte Carlo model [*Tucker and Johnson*, 2009] produces exospheric fluxes similar to the corresponding Jeans flux. Such enhancements are of interest as large upward flows of CH_4 and N_2 have been suggested when applying the 1D continuum equations to Titan's thermosphere [*Yelle et al.*, 2008; *Strobel*, 2008]. Because rates consistent with the Cassini INMS data base have been debated (e.g., O. J. Tucker et al., Diffusion and thermal escape of H_2 from Titan's atmosphere: Monte Carlo Simulations, submitted to *Icarus*, 2012), here we show that the thermospheric wind speeds of the size derived by M-WYCW at Titan need to be considered when describing atmospheric escape, especially, and possibly surprisingly, the horizontal winds. These estimates emphasize that escape in the presence of high wind speeds is a 3-dimensional problem that should include the global density, temperature and wind fields at the exobase.

2. Escape due to Winds at the Exobase

[5] Because a large fraction of escaping atoms and molecules originate well below the exobase, as confirmed by kinetic Monte Carlo simulations, the coronal and escaping neutrals are collisionally coupled to the thermospheric flow fields. Therefore, the speed distribution of neutral particles at exobase altitudes is displaced by a neutral wind. This results in an escape flux that exceeds the thermal escape flux from a static atmosphere, whether estimated by the Jeans flux, F_J, or calculated using a kinetic model. This is the case for all horizontal winds and outgoing radial winds, but the escape

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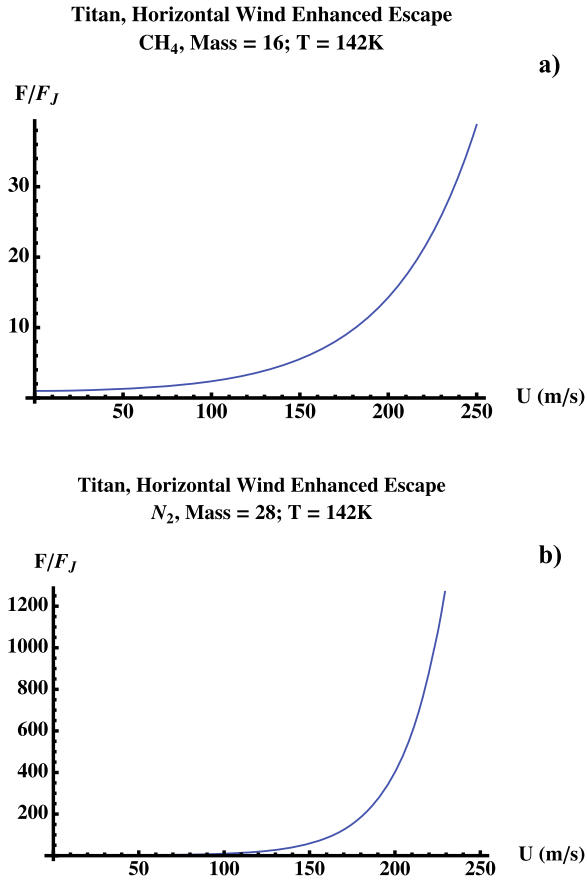
Titan, Horizontal Wind Enhanced Escape
CH_4, Mass = 16; T = 142K

a)

Titan, Horizontal Wind Enhanced Escape
N_2, Mass = 28; T = 142K

b)

Figure 1. Ratio of wind-enhanced escape flux, F, divided by the Jeans escape flux, F_J, versus the horizontal wind speed, U, at 142 K, (a) for methane, CH_4, and (b) for molecular nitrogen, N_2.

rate is reduced when the wind is incoming radially. This was pointed out in *Hartle* [1971] and, within the Jeans approximation, was made explicit in HM. They calculated the flux $F_{kh}(u)$ of the k-th species with the normalized horizontal winds u in an atmosphere in local thermal equilibrium by adding a horizontal wind to the Maxwellian velocity distribution function at the presumed exobase and obtained

$$F_{kh}(u) = \frac{N(k)e^{-u^2}}{\pi^{1/2}\gamma^{1/2}}\left[e^{-\lambda} \int_0^{\lambda^{1/2}} yI_0(2uy)dy + \int_{\lambda^{1/2}}^{\infty} ye^{-y^2} I_0(2uy)dy \right]$$

(1)

In equation (1) $I_0(x)$ is the modified Bessel function, N(k) is the exobase density of the k-th species, $\lambda = mMG/RkT$ is the Jeans parameter and $1/\gamma = 2\,kT/m$ is the most probable speed squared. Here m is the particle mass, G the gravitational constant, k the Boltzmann's constant, and M, R and T the mass, exobase radius, and base exospheric temperature, respectively. HM give a similar expression for the effect of the vertical wind speed. As can be seen in Figures 12 and 14 of M-WYCW, the horizontal wind speed, U, at Titan is generally much larger than vertical wind speed. In equation (1), U has been normalized by the most probable thermal speed $u = \gamma^{1/2}U$. The enhancement due to upward flow is often considered [*Yelle*

et al., 2008; *Volkov et al.*, 2011] but the effect of horizontal flows has been mostly ignored.

[6] By integrating equation (1), HM found that as the wind velocity increases, the escape flux increases above the Jeans flux, $F_{kJ} = \frac{N(k)}{2\sqrt{\pi}\gamma}(1 + \lambda)e^{-\lambda}$. Recent molecular kinetic simulations, that are equivalent to solving the Boltzmann, indicate that the Jeans expression can underestimate the thermal escape rate by ~1.5 to about a factor of two for $\lambda \sim 15$ to 4 [*Tucker and Johnson*, 2009; *Volkov et al.*, 2011] with much smaller corrections for much larger λ. However, the ratio of the thermal escape rate to the wind enhanced rate would be similar to that using to F_{kh}/F_{kJ} above. Here we point that the horizontal winds provide a *further* enhancement. Therefore, we first estimate the enhancement for an atmosphere in which the velocity distribution function is nearly Maxwellian at the exobase, but has an added horizontal flow speed; that is, we will first consider the ratio F_{kh}/F_{kj} using equation (1) and the Jeans flux. The size of F_{kh}/F_{kj} is found to increase as u increases *and* as the Jeans parameter λ increases. As the Jeans parameter increases, F_{kj} decreases rapidly. Therefore, the enhancement is primarily important for the certain species, as shown in HM for escape of He from Earth.

[7] For the application to Titan, the temperature, T, and densities, N(k), are chosen from M-WYCW. For a nominal exobase radius of 4000 km (used throughout, altitude is 1425 km), M-WYCW give a temperature T = 142°K (their Figure 11). The corresponding Jeans parameters are $\lambda(N_2) = 53.5$, $\lambda(CH_4) = 30.6$ and $\lambda(H_2) = 3.82$. At this temperature, the enhancements over the Jeans rate are shown in Figure 1a for CH_4 and Figure 1b for N_2 as a function M-WYCW of the horizontal wind U. The range of wind speeds exhibited are consistent with those in M-WYCW, including speeds as high as 250 m s^{-1} found when waves are considered [*Müller-Wodarg et al.*, 2006]. For both constituents, the enhancement increases as the wind speed increases. For the Jeans parameters above, the enhancements are large: ~58x and ~5.5x at 150 m s^{-1} or ~2860x and ~39x at 250 m s^{-1} for N_2 and CH_4, respectively. For H_2, the enhancement is much smaller: ~3% at 150 m s^{-1} and ~8% at 250 m s^{-1}. Until a more detailed thermosphere model is calculated, the minor gases CH_4 and H_2 are assumed to have the horizontal velocities of the major gas N_2. This is a conservative assumption because lighter gases like H_2 frequently move faster horizontally. If one allows that the H_2 horizontal speed could be as much as its thermal speed, 1090 cm s^{-1} at 142 K, then the enhancement $F/F_J = 2.7$ is a value close to that suggested by the analysis of the diffusion equations in *Cui et al.* [2008, 2011], although recent kinetic Monte Carlo modeling questions that analysis (Tucker et al., submitted manuscript, 2012).

[8] Using data for the relatively high temperature T36 flyby, ~188 K [*Westlake et al.*, 2011], the Jeans parameters and densities evaluated at the exobase are $\lambda(N_2) \sim 40.5$, $\lambda(CH_4) \sim 23$ and $\lambda(H_2) \sim 3$ and $N_{N_2} \sim 10^7$ cm^{-3}, $N_{CH_4} \sim 5 \times 10^6$ cm^{-3}, $N_{H_2} \sim 10^6$ cm^{-3} as global averages, then the Jeans rates are $F_{N_2,J} \sim 10^{14}$ N_2 s^{-1}, $F_{CH_4,J} \sim 10^{22}$ CH_4 s^{-1}, and $F_{H_2,J} \sim 10^{28}$ H_2 s^{-1}. In addition to the correction of ~1.5–2 suggested by the kinetic modeling [e.g., *Volkov et al.*, 2011], the enhancements are 58.3, 5.53 and 1.03, respectively, for a 150 m/s wind and 2860, 38.8 and 1.08, respectively, for a 250 m s^{-1} wind. However, with the
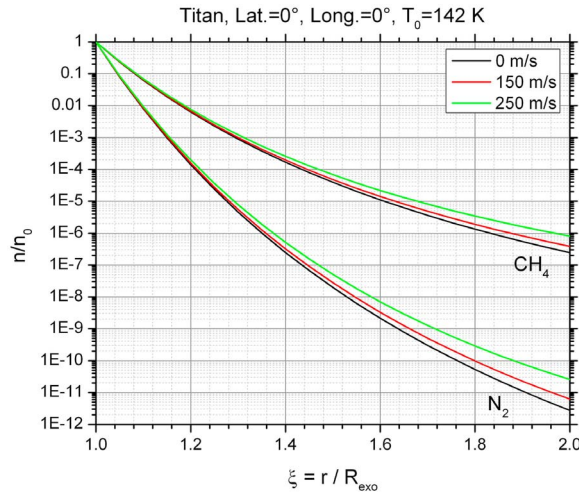
Figure 2. Density profiles of exospheric N_2 and CH_4 are shown. Exospheric densities, n, normalized by their exobase values, n_0, versus the radial distance, r, normalized by the exobase radius, $R_{exo} = 4000$ km.

exception of H_2, the net escape fluxes are likely smaller than a number of estimates [e.g., *Johnson et al.*, 2009; Tucker et al., submitted manuscript, 2012].

[9] The flux enhancements due to winds also affect the N_2 and CH_4 density profiles at large distances from the exobase where ion pick-up and sweeping occur. Again assuming a ballistic atmosphere determined by a Maxwellian speed distribution at the exobase, these are shown in Figure 2 as a function of r/R_{exo} for three wind speeds: 0, 150, and 250 m s^{-1}. For a given wind speed, the size of the enhancement increases with distance above the exobase. For example, at twice the exobase radius, or ~8000 km, the N_2 density increases due to 150 and 250 m s^{-1} winds are ~2.1x and ~10x the density with no wind, respectively. Similarly, CH_4 increases are ~1.6x and ~3.3x. Such differences can affect the estimate of Titan's interaction with the plasma trapped in Saturn's magnetosphere, which in turn can affect the heating rate of the upper atmosphere. In addition, the density at ~4000 km above the exobase are ~2 × 10^{-4} cm^{-3} for N_2 and ~1.5 cm^{-3} for CH_4, which are observable by the Cassini UVIS spectrometer [*Esposito et al.*, 2004].

3. Discussion

[10] Unlike the *thermal escape* of He at the Earth in HM, the molecular masses and gravitational binding at Titan are such that the wind-enhanced *Jeans rates* are relatively small except for H_2. But for this case the enhancement may be small. Pluto's atmosphere, which has a composition similar to that of Titan and is soon to be visited by New Horizon, could also have high thermospheric wind speeds due to non-uniform solar heating. Although the exobase temperature is lower, its mass is much small than Titan's so the Jeans parameter is much smaller. Using the result of the recent 1D single component fluid/ hybrid model for thermal escape at near solar minimum conditions (r_{exo} ~ 6200 km; n_{N2} ~ 10^5 N_2 cm^{-3}, $\lambda(N_2)$ ~ 5.4 [*Tucker et al.*, 2012]), the already large global escape rate (~1 × 10^{27} N_2 s^{-1}) would be

enhanced by factors of 1.4 and 2.1 for thermospheric wind speeds ~100 m s^{-1} and 150 m s^{-1}, respectively, using equation (1). This would further expand the already very highly extended upper atmosphere proposed in *Tucker et al.* [2012].

[11] At Titan we know that non-thermal processes occurring in the magnetosphere/atmosphere system cause the tail of the neutral speed distribution to differ from a Maxwellian [e.g., *Johnson et al.*, 2009]. A horizontal wind can also affect the estimate of the escape rate when the speed distribution near the exobase is non-thermal. In *De La Haye et al.* [2007] kappa distributions at the exobase were used in Monte Carlo simulations to fit the INMS data *above* the nominal exobase. Such distributions have power law tails, $f(v) \rightarrow c/v^q$ at large v, consistent with non-thermal processes being active. Rather than using the full speed distribution, we make a simple estimate of the enhancement for $q > 4$ and $v > v_t$, where v_t is the speed at which the power law evolves into the Maxwellian core. Here c is determined by the fraction of molecules in the tail, F_t. Therefore, for an isotropic velocity distribution $f(v) = c/v^q = F_t [(q - 3)/4\pi] v_t^{q-3} /v^q$. Integrating over $f(v)$ for $v \geq v_{esc} > v_t$, the escape flux is $\phi_{esc} = n\, v_{esc}\, F_t\, [(q - 3)/4(q - 4)]\, (v_t/v_{esc})^{q-3}$. In the presence of a horizontal wind, the escape flux becomes

$$\varphi_{esc+} = (n/2)F_t[(q-3)/(q-4)4\pi]v_t^{q-3} \int_0^{2\pi} d\varphi/v(\varphi)^{q-4}, \quad (2)$$

where φ is the angle between the velocity, v, from the isotropic distribution and the flow indicated by the horizontal wind, u. Writing $x(\varphi) = v(\varphi)/v_{esc}$, where $x(\varphi) = -x_h \cos\varphi \pm [1 - x_h^2 (\sin\varphi)^2]^{0.5}$, with $x_h = u/v_{esc}$ the flux enhancement can be written: $\frac{\phi_{esc+}}{\phi_{esc}} = \frac{1}{2\pi} \int_0^{2\pi} \frac{d\varphi}{x(\varphi)^{q-4}}$. Integrating this expression for various wind speeds, v_h, and q's, we find $\varphi_{esc+}/\varphi_{esc}$ can be large, and increases monotonically as q increases. For example, when u = 150 and 250 m s^{-1} at Titan and q is large: u = 150 m s^{-1}, $\varphi_{esc+}/\varphi_{esc}$ = 9, 30 and 236 when q = 50, 70 and 100, respectively and u = 250 m s^{-1}, $\varphi_{esc+}/\varphi_{esc}$ = 50 and 1000 when q = 50 and 70, respectively.

[12] Using data from a few early Cassini passes through Titan's atmosphere, *De La Haye et al.* [2007] showed the exosphere is highly variable so that at times its vertical structure is *not* suggestive of non-thermal processes. At these times the escape rates for N_2 or CH_4 are like those discussed above. In addition, the altitude range of the data analyzed was limited, the INMS densities were under estimated by about a factor of 3, enhancing the De La Haye et al. escape estimates, and the egress data were apparently affected by molecular accumulation on the walls of the instrument [*Teolis et al.*, 2010]. However, a non-thermal tail appeared to be required to describe the vertical structure of the exosphere for ingress pass TA. It was present in both the N_2 and CH_4 and could be roughly characterized by kappa distributions in which the q above is ~30 and ~18 respectively giving enhancements of ~18 and ~1.6. Therefore, obtaining an accurate rate *requires* that one does not ignore the effect of the thermospheric winds.

[13] Although there are uncertainties in the actual escape rates at Titan for all 3 species, models for the escape of methane exhibit the largest discrepancies. These uncertainties might not be surprising, since the structure of the upper atmosphere is highly variable and methane is a minor species with a significant mass and escape of H_2 cools the background so that the CH_4 profile is not hydrostatic (Tucker et al., submitted manuscript, 2012). Here we point out that for those cases and time periods for which the methane escape rates are significant, the presence of thermospheric winds can result in an enhancement factor of ~ 2 to an order of magnitude. Unfortunately, new kappa fits to the corrected and very large INMS data set for Titan's corona are not yet available.

[14] It has been shown often that calculating escape by going from the collision dominated regime into the exosphere requires a kinetic model [e.g., *Hartle*, 1973; *Tucker and Johnson*, 2009; *Tucker et al.*, 2012, also submitted manuscript, 2012]. In addition, a drifting Maxwellian below the exobase has been shown to evolve smoothly into the collisionless domain at higher altitudes, yielding a non-Maxwellian distribution while retaining the signature of the wind [*Curtis and Hartle*, 1977]. Such a transition is not well described by 1D continuum descriptions. We also note that the large *upward* flux of molecules required by 1D diffusion models for CH_4 to fit the highly variable INMS data for some Cassini passes *might not* be associated with molecules *only* on escape trajectories. Rather they can have a horizontal component that allows the gas to flow *downward* at some other point on the globe. This is the case for the thermosphere simulations of *Müller-Wodarg et al.* [2006, 2008], which take into account the density and temperature variations observed around the globe and self-consistently produce thermospheric winds. Therefore, the full upward flux estimated from 1D diffusion models for CH_4 in the atmosphere of Titan neglecting coupling to the escape of H_2 [e.g., *Yelle et al.*, 2008] should be thought of as upper bounds on the escape rate. As suggested by the high spatial and temporal variability in the INMS data and the results above, the effect of the resulting horizontal flow *must* be included to correctly calculate the CH_4 escape flux at Titan. Clearly 3D thermospheric flow simulations that couple to multispecies kinetic models in the exobase region will eventually be needed. Since this is very challenging computationally, here we give a means to estimate the wind-induced enhancement for thermal or non-thermal escape. Recently it has also been shown, not surprisingly, that exoplanets that orbit close to their parent star are likely to have high speed thermospheric winds [e.g., *Montalto et al.*, 2011]; these also will affect the estimates of the atmospheric escape rate.

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